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Sensitivity Study of Monte Carlo burnup calculations of two pebble-bed fluoride-salt-cooled high-temperature reactors

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1. Introduction

The ordered pebble bed fluoride salt-cooled high temperature reactor is a design concept for fluoride salt-cooled high temperature reactor (FHR) with ordered packed pebbles. The pebbles contain thousands of micro-fuel particles called Tristructural isotropic (TRISO) particles. The pebble bed FHR catches much attention as it features low-pressure liquid fluoride salt cooling, coated-particle fuel, a high-temperature power cycle, and fully passive decay heat rejection[1-2]. The ordered-pebble bed reactor is proposed to reduce the difficulties of fueling and defueling. Without the pebble bed flowing, the reactor core is stable. As the location of the fuel pebbles in the core is determined, the uncertainty of the neutron physics, thermal fluid analysis and safety analysis is reduced. The core naturally forms measurement channels, enabling experiments and data measurements.

Burnup calculations are important parts of the reactors' designs. For ordered pebble bed -FHR, each pebble is in its fixed position in lifetime. If the fuel composition of each fuel pebble and the composition of structure materials at the moment are known, the fission power distribution and neutron spectrum can be obtained. The fuel composition of each fuel pebble and the composition of structure materials at next moment can thus be conducted. In theory, the fuel composition of each fuel pebble and the composition of structure materials can be obtained by carrying out this procedure continuously. As the Monte Carlo neutron transport calculations are time and memory costing, the numbers of burnup zones are limited. The question of how to divide the active core is worthy of study. A primary estimation of effective multiplication factor and life time of reactor core can be conducted by the burnup calculation with the whole active core being one burnup zone. However, the calculated neutron spectrum, neutron flux density distribution, and fission power distribution with different numbers of burnup zones gradually dissimilated over time with nuclear burning. In order to make the calculation closer to the reactor, the burnup with zones should be applied. It is of interest to find out how to improve efficiency while ensuring enough accuracy.

In the following chapters, the burnup calculations methods and the model construction will be introduced and discussed. The calculation methods are then applied to two typical reactors of ordered pebble bed FHR: 1GWt ordered pebble bed FHR and 2MWt order pebble bed FHR. The results obtained by the burnup calculations with different number of burnup zones are compared with each other.

2. Calculation Methods

It is of interest to find out how to improve efficiency while ensuring enough accuracy. One can see that decrease the number of zones can improve the efficiency of Monte Carlo neutron transport calculation obviously. At the same time, the type of division should reflect the burnup of fuel, which means to put the fuel with near composition in one burnup zone. The change of composition is positive correlated the local fission power. It is reasonable to assign the pebbles with close fission power to the same burnup zone. Although the fission power distribution changes with reactor operation time, the difference of the fuel composition is lower than those in different zones as the burnup are closer. The burnup of fuel is deeper in the region with high fission power. It should be noticed that the difference of fuel composition would not increase without limit in real reactor.

The TRISO fuel particles in the pebbles consist of a fissile material (such as enriched uranium) surrounded by a coated ceramic layer of silicon carbide for structural integrity and fission product containment. In the calculation, homogenization of TRISO particle coatings with the carbon matrix while keeping each fuel kernel. The model with homogenized layers maintains effective multiplication factor and similar to the fully heterogeneous model. In the models the fuel kernels are not randomly distributed but are modeled as simple cubic lattice. It was found that the differences in reactivity are negligible for the calculated results with the fuel kernels modeled as simple cubic lattice, body centered cubic lattice, and face centered cubic lattice[3]. The TRISO particles are dispersed in a graphite matrix that is enclosed in a hard graphite shell. The pebbles are ordered packing by rectangular lattice in the fixed position in the active core of the ordered pebble bed FHR. The coolant selected for pebble bed FHR is LiF-BeF_2, commonly referred to as flibe.

The neutronic calculations were performed using the SCALE code package version 5.1[4,5]. The neutron transport calculations were performed using the full 3-D code KENOVI with the multigroup options. The TRITON module executes a sequence of modules from the SCALE packag. The multigroup cross-section libraries thus created are further used in the KENO-VI module to generate a transport solution (fluxes and eigenvalue) for the system, which is further post-processed by KMART. Finally, the fluxes from the transport calculations are used (after preparation by COUPLE) in the ORIGEN-S code to deplete the fuel. These steps are repeated then for the next time step until the time evolution of the system

3. Results and Discussion

3.1 1GWt ordered pebble bed FHR

The sectional view of the 1GWt ordered pebble bed FHR core is presented in Fig. 1. The active core is an octagonal prism. The distances between opposite sides are 4.96 m and 5.01m. The height of the active core is 5.01 m. The 141 layers consist of 588071 of fuel pebbles. The packing factor of TRISO is 7.03%. The enrichment of Uranium is 17.8%. Fig. 2 shows the fission power of the same fission materials at the beginning of the life time.

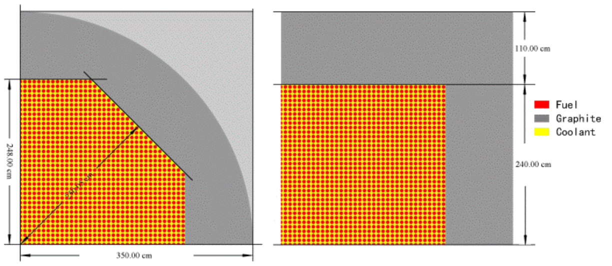

Fig. 1. The cross sectional view of the 1GWt ordered pebble bed FHR core

Based on the calculation results, the active core is divided into burnup zones. Fig. 3 shows the burnup zones of 1GWt ordered pebble bed FHR active core. In the 4 burnup zone calculations, the zone 1, zone 2, zone 3, zone 4 are presented by red, purple, blue, dark blue, respectively. In the 2 burnup zone calculations, the zone 1 is presented by red or purple, the zone 2 is presented by blue or dark blue. The zigzags are caused by the error in the fission power calculation. The burnup calculations are carried out by SCALE5.1 code package included by effective multiplication factor and the fuel composition with time. Fig. 4 represent the calculated effective multiplication factor with time. It can be seen that the difference of effective multiplication factor is very turns larger gradually. The difference keeps a constant after the burnup is higher than 5 GWd/MTHM. The average of the difference between 1 zone calculations and 2 zone calculations is 0.00361 when the burnup is higher than 5 GWd/MTHM, much larger than the average of the difference between 2 zone calculations and 4 zone calculations (0.00021). The difference of discharge burnup is about 1 GWd/MTHM.

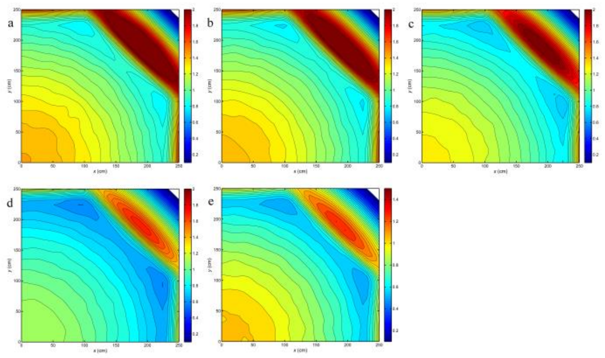

Fig. 2. The fission power of the same fission materials at the beginning of the life time.

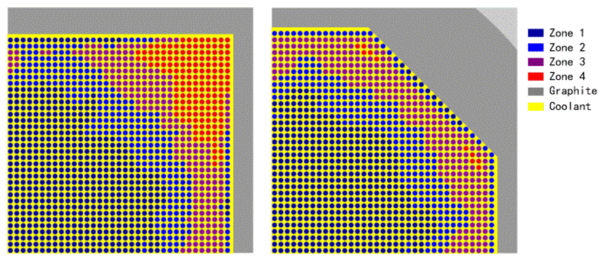

Fig. 3. The cross sectional view of burnup zones of 1GWt ordered pebble bed FHR active core.

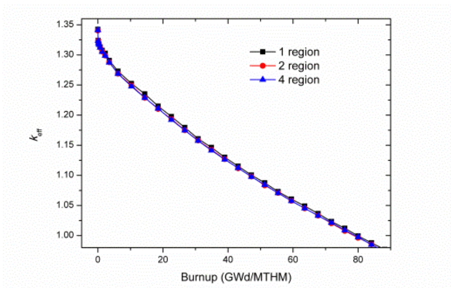

Fig. 4. The effective multiplication factor of 1GWt ordered pebble bed FHR with time.

The calculated fuel composition is showed in Fig. 5. It can be seen that the difference of ^{235}U composition is large than 15%. The 4 zone calculation can reflect the concentration of fission nuclear difference in different regions. At the same time, the difference of concentration of the ^{135}Xe in different zones becomes smaller (near zero) at the end of life time. It indicates that the fission power is flattened by the different fuel consumption rate can reduce the difference of fission power in different regions.

It is of interest to find out the difference of calculated fission power distributions in the end of life time. Fig. 6 show the fission power distribution based on the 1 zone, 2 zone and 4 zone burnup calculations. It can be seen that the fission power peak of 1 zone calculation conducted fission power distribution is in the middle of the active core, while the fission power peak of 2 zone or 4 zone calculation conducted fission power distribution is far from the middle. The distributions calculated by 2 zone and 4 zone calculation are similar.

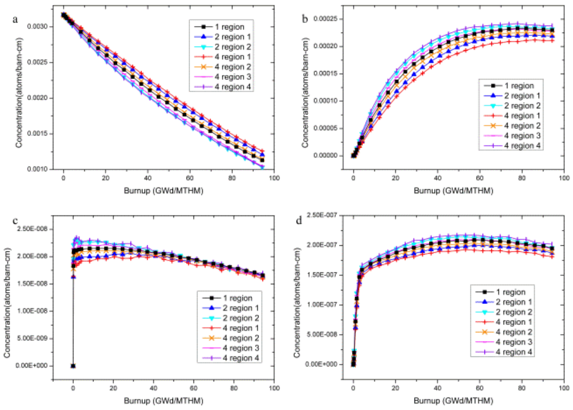

Fig. 5. The fuel composition with time.

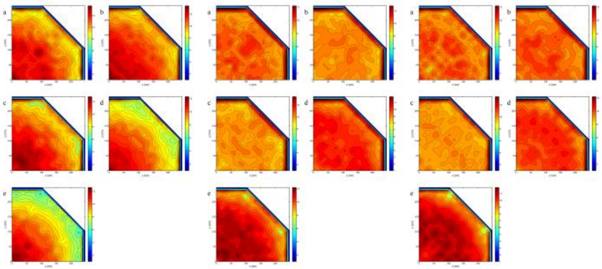

Fig. 6. The fission power distribution based on the 1 zone, 2 zone, and 4 zone burnup calculations.

It is concluded that 1 zone calculation can only estimate the effective multiplication factor and life time of the 1GWt reactor, while the error of the power distribution is large. The 2 zone calculation and 4 zone calculation are very similar, indicating that 4 zone calculation can fulfill the requirements of precision.

3.2 2MWt ordered pebble bed FHR

The sectional view of the 2MWt ordered pebble bed FHR core is presented in Fig. 7. The active core is an octagonal prism with a square cylinder in the middle. The distances between opposite sides are 153.0 cm and 154.5 cm. The side length of the square cylinder is 36 cm. 5 channels are in the cylinder. The height of the active core is 168.78cm. The 47 layers consist of 16924 of fuel pebbles. The packing factor of TRISO is 7.03%. The enrichment of Uranium is 17.8%. Fig. 8 shows the calculated fission power distribution at the beginning of the life time. It should be noticed that there is no fission power in reflector. The high fission power in the reflector is calculated by assuming that there are the same fission materials in the region. Based on the calculation results, the active core is divided into burnup zones. Fig. 9 shows the burnup zones of 2MWt ordered pebble bed FHR active core. In the 4 burnup zone calculations, the zone 1, zone 2, zone 3, zone 4 are presented by red, purple, blue, dark blue, respectively. In the 2 burnup zone calculations, the zone 1 is presented by red or purple, the zone 2 is presented by blue or dark blue.

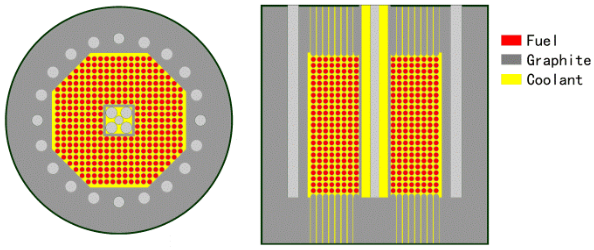

Fig. 7. The cross sectional view of the 2MWt ordered pebble bed FHR core.

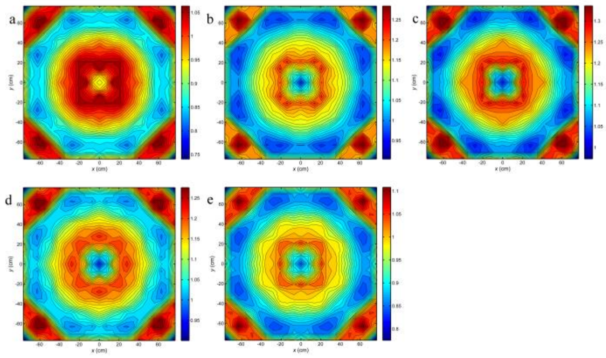

Fig. 8. The fission power fission power of the same fission materials at the beginning of the life time.

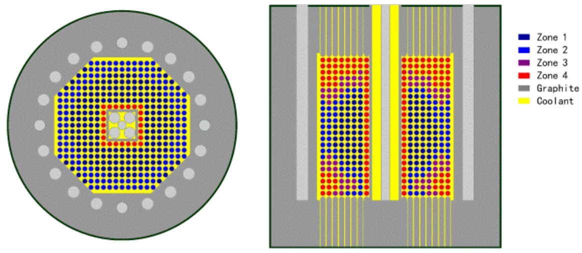

Fig. 9. The cross sectional view of burnup zones of 2MWt ordered pebble bed FHR active core.

The burnup calculations are carried out by SCALE5.1 code package included by effective multiplication factor and the fuel composition with time. Fig. 10 represent the calculated effective multiplication factor with time. It can be seen that the difference of effective multiplication factor is turns larger gradually and keeps a constant after the burnup is higher than 10 GWd/MTHM. The average of the difference between 1 zone calculations and 2 zone calculations is 0.001359 when the burnup is higher than 10 GWd/MTHM, much smaller than the calculation results of 1GWt ordered pebble bed FHR. The difference between 2 zone calculations and 4 zone calculations are 0.00016, similar to the random error of Monte Carlo calculations. The difference of discharge burnup is about 0.7 GWd/MTHM, a little bit smaller than that of 1GWt ordered pebble bed FHR. The discharge burnup of 2MWt ordered pebble bed FHR is much smaller than that of 1GWt pebble bed FHR.

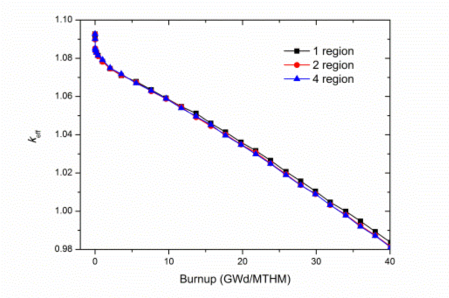

Fig. 10. The effective multiplication factor with time.

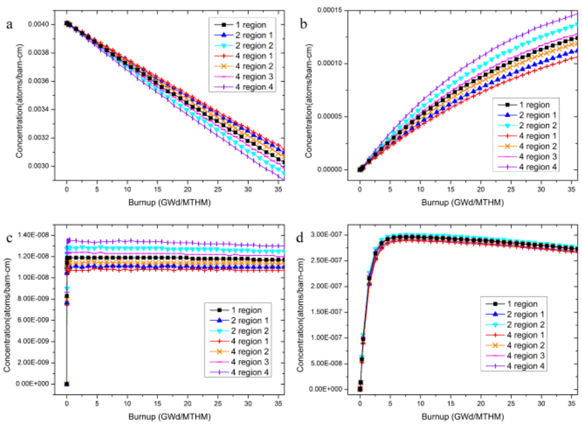

Fig. 11. The fuel composition with time.

The calculated fuel composition is showed in Fig. 11. It can be seen that the difference of ^{235}U composition is about 6%, indicating that the difference in different regions in the 2MWt ordered pebble bed FHR is much smaller than that of 1GWt ordered pebble bed FHR. The difference of concentration of ^{135}Xe in different zones becomes only a little smaller at the end of life time.

It is of interest to find out the difference of calculated fission power distributions in the end of life time. Fig. 12, presents the fission power of the burnup zones based on the 1 zone, 2 zone and 4 zone burnup calculations. It can be seen that the fission power of the burnup zones do not change much. The order of the fission power keeps the initial state. This phenomenon may be caused by the low discharge burnup of the 2MWt ordered pebble bed FHR.

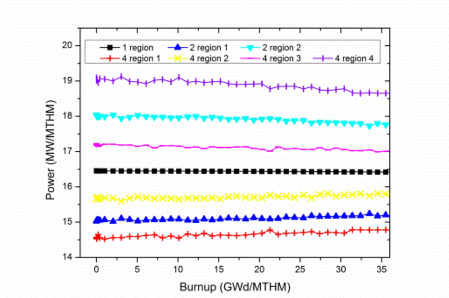

Fig. 12. The fission power in different burnup zones.

It is concluded that 1 zone calculation can conduct the reasonable estimate of effective multiplication factor and life time of the 2MWt reactor, while error of the power distribution is larger. The fission power distribution do not change much 2 zone and 4 zone calculations, indicating that 4 zone calculation can fulfill the requirements of precision in preconception calculation.

4. Conclusions

In summary, 1 zone burnup calculation can only estimate of effective multiplication factor and life time of the reactor core. For 1GWt pebble bed FHR, the average of the difference between 1 zone calculations and 2 zone calculations is 0.00361 when the burnup is higher than 5 GWd/MTHM, much larger than the average of the difference between 2 zone calculations and 4 zone calculations (0.00021). For 2MWt pebble bed FHR, the average of the difference between 1 zone calculations and 2 zone calculations is 0.001359 when the burnup is higher than 10 GWd/MTHM, much smaller than the calculation results of 1GWt ordered pebble bed FHR. The difference between 2 zone calculations and 4 zone calculations are 0.00016, similar to the random error of Monte Carlo calculations.

The calculated power distribution of 1 zone calculation differs from the 2 zone or 4 zone calculations for the 1GWt reactor. The 2 zone calculation and 4 zone calculation are very similar, indicating that 4 zone calculation can fulfill the requirements of precision. For 2MWt reactor, the fission power distribution do not change much by 1 zone, 2 zone and 4 zone calculation, indicating that 2 zone calculation can fulfill the requirements of precision in the calculation.

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